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Improved Measurements of Branching Fractions for $B^0 \to \pi^+\pi^-$, $K^+\pi^-$, and Search for K^+K^- at BABAR

The BABAR Collaboration

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Abstract

We present preliminary measurements of branching fractions for the charmless two-body decays $B^0 \to \pi^+\pi^-$ and $K^+\pi^-$, and a search for $B^0 \to K^+K^-$ using a data sample of approximately 227 million $B\overline{B}$ decays. Signal yields are extracted with a multi-dimensional maximum likelihood fit, and the efficiency is corrected for the effects of final-state radiation. We find the charge-averaged branching fractions (in units of 10^{-6}):

$$\mathcal{B}(B^0 \to \pi^+\pi^-) = 5.5 \pm 0.4 \pm 0.3, \tag{1}$$

$$\mathcal{B}(B^0 \to K^+\pi^-) = 19.2 \pm 0.6 \pm 0.6, \tag{2}$$

$$\mathcal{B}(B^0 \to K^+K^-) = < 0.40. \tag{3}$$

The errors are statistical followed by systematic, and the upper limit on K^+K^- represents a confidence level of 90%.

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1 INTRODUCTION

Charmless hadronic two-body B decays to pions and kaons provide a wealth of information on CP violation in the B system, including all three angles of the unitarity triangle. The time-dependent CP asymmetries in the $\pi\pi$ system can be used to measure the angle α [1]; the decay rates for the $K\pi$ channels provide information on γ [2]; and the time-dependent CP asymmetry in $\pi^0 K^0_S$ approximately measures β in the standard model [3] and is a sensitive probe of new physics in the $b \to s$ penguin-decay process [4]. Recently, direct CP violation in decay was established in the B system through observation of a significant rate asymmetry between $B^0 \to K^+\pi^-$ and $\overline{B}^0 \to K^-\pi^+$ [5, 6]. As B-physics experiments accumulate much larger data sets, charmless two-body B decays will continue to play a critical role in testing the standard model description of CP violation.

In order to extract the maximum information from these decays it is necessary to understand the underlying hadron dynamics, and measurements of branching fractions for all of the charmless two-body B decays involving combinations of $\pi^{\pm}$, $K^{\pm}$, π^0, and K^0_S are invaluable in testing the various theoretical approaches [7]. We present preliminary measurements of branching fractions for the decays [8] $B^0 \to \pi^+\pi^-$ and $K^+\pi^-$, and a search for the decay $B^0 \to K^+K^-$ using a data set 2.5 times larger than the one used for our previous measurements of these quantities [9]. Table 1 summarizes previous experimental measurements [9, 10, 11] and current theoretical estimates of the branching fractions for these decays.

2 THE *BABAR* DETECTOR AND DATASET

The data sample used for this search contains $(226.6 \pm 2.5) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected by the *BABAR* detector [12] at the SLAC PEP-II e^+e^- asymmetric-energy storage ring. The primary detector components used in the analysis are a charged-particle tracking system consisting of a five-layer silicon vertex detector and a 40-layer drift chamber surrounded by a 1.5-T solenoidal magnet, and a dedicated particle-identification system consisting of a detector of internally reflected Cherenkov light (DIRC) providing K–π separation over the range of laboratory momentum relevant for this analysis (1.5–4.5 GeV/c).

Table 1: Summary of existing branching fraction measurements (in units of 10^{-6}) and theoretical estimates for the decays $B^0 \to \pi^+\pi^-$, $K^+\pi^-$, K^+K^-. Theory estimates are from Beneke *et al.* and Keum in Ref. [7].

Mode	$\mathcal{B}$(*BABAR*) [9]	$\mathcal{B}$(Belle) [10]	$\mathcal{B}$(CLEO) [11]	Theory
$\pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$4.4 \pm 0.6 \pm 0.3$	$4.5^{+1.4}_{-1.2}{}^{+0.5}_{-0.4}$	4.6-11.0
$K^+\pi^-$	$17.9 \pm 0.9 \pm 0.7$	$18.5 \pm 1.0 \pm 0.7$	$18.0^{+2.3}_{-2.1}{}^{-1.2}_{-0.9}$	12.7-21.0
K^+K^-	< 0.6	< 0.7	< 0.8	0.007-0.080

Table 2: Summary of total detection efficiencies (%) for signal decays determined in GEANT Monte Carlo samples without FSR effects, compared with the results using PHOTOS and the leading-order QED calculation. We use the latter result in calculating the branching fraction and take the difference with PHOTOS as the systematic uncertainty. Uncertainties are statistical only.

Mode	No FSR	PHOTOS	QED
$\pi^+\pi^-$	40.9 ± 0.2	39.9 ± 0.2	39.4 ± 0.2
$K^+\pi^-$	39.9 ± 0.2	38.9 ± 0.2	38.4 ± 0.2
K^+K^-	38.6 ± 0.3	37.8 ± 0.3	37.6 ± 0.3

3 ANALYSIS METHOD

The data sample used in this analysis is similar to that used in the *BABAR* measurements of direct *CP* violation in $K^+\pi^-$ [5] and time-dependent *CP*-violating asymmetry amplitudes $S_{\pi\pi}$ and $C_{\pi\pi}$ [13] (the reader is referred to those references for further details on the analysis technique). Relative to the event selection applied in the *CP* analyses, we remove the requirement on the difference in the decay times (Δt) between the two B mesons in order to minimize systematic uncertainty on the branching fraction measurements. All other selection criteria are identical to those applied in Refs. [5, 13]. We identify $B \to h^+h^-$ ($h = \pi$ or K) candidates with selection requirements on track and Cherenkov-angle (θ_c) quality, B-decay kinematics, and event topology, and determine signal and background yields through a multi-dimensional maximum-likelihood fit. The final sample contains 69264 events and is defined by requirements on the energy difference, $|\Delta E| < 150\,\mathrm{MeV}$, and energy-substituted mass, $5.20 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}/c^2$, of the selected B candidates [14].

The efficiency of the selection criteria is determined in large samples of GEANT-based Monte Carlo simulated signal decays. We include the effects of electromagnetic radiation from charged particles using the PHOTOS simulation package [15]. The addition of final-state radiation (FSR) leads to the development of a low-energy tail in the distribution of ΔE for $B^0 \to h^+h^-$ signal candidates, which can cause some fraction of events to fail the $|\Delta E| < 150\,\mathrm{MeV}$ requirement. We have implemented a detailed QED calculation [16] up to $\mathcal{O}(\alpha)$ in order to correct the efficiency obtained by the PHOTOS simulation. Table 2 summarizes the comparison of the efficiencies for the different modes assuming no FSR, the PHOTOS result, and the QED calculation. For the branching fraction measurement we use the efficiency as determined by the QED calculation, and take the difference with respect to PHOTOS as the systematic uncertainty.

In addition to signal $\pi^+\pi^-$, $K^+\pi^-$, and (possibly) K^+K^- events, the selected sample includes background from the process $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$). Possible backgrounds from other B decays are small relative to the signal yields ($< 1\%$), and are treated as a systematic uncertainty. We use an unbinned, extended maximum-likelihood fit to extract simultaneously signal and background yields in the three topologies ($\pi\pi$, $K\pi$, and KK). The fit uses the discriminating variables m_{ES}, ΔE, θ_c, and the Fisher discriminant $\mathcal{F}$ described in Ref. [9], where the likelihood for event j is obtained by summing the product of the event yield n_i and probability $\mathcal{P}_i$ over the signal and background hypotheses i. The total likelihood for the sample is

$$\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_j \left[\sum_i n_i \mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i)\right]. \tag{4}$$

The probabilities $\mathcal{P}_i$ are evaluated as the product of the probability density functions (PDFs) with parameters $\vec{\alpha}_i$, for each of the independent variables $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-\}$, where θ_c^+ and θ_c^- are the Cherenkov angles for the positively- and negatively-charged tracks, respectively. The largest correlation between the $\vec{x}_j$ is 13% for the pair $(m_{\rm ES}, \Delta E)$ and we have confirmed that it has negligible effect on the fitted yields. For both signal and background, the $K^{\pm}\pi^{\mp}$ yields are parameterized as $n_{K^{\pm}\pi^{\mp}} = n_{K\pi}\left(1 \mp \mathcal{A}_{K\pi}\right)/2$, and we fit directly for the total yield $n_{K\pi}$ and the asymmetry $\mathcal{A}_{K\pi}$. The result for $\mathcal{A}_{K\pi}$ is used only as a consistency check and does not supersede our previously published result [5].

The eight parameters describing the background shapes for $m_{\rm ES}$, ΔE, and $\mathcal{F}$ are all allowed to vary freely in the maximum-likelihood fit. We use a threshold function [17] for $m_{\rm ES}$ (1 parameter), a second-order polynomial for ΔE (2 parameters), and a sum of two Gaussian distributions for $\mathcal{F}$ (5 parameters). For the signal shape in $m_{\rm ES}$, we use a single Gaussian distribution to describe all three channels and allow the mean and width to vary freely in the fit. For ΔE, we use the sum of two Gaussian distributions (core + tail), where the core parameters are common to all channels and allowed to vary freely, and the tail parameters are determined separately for each channel from Monte Carlo simulation and fixed in the fit. Given that the tail is dominated by FSR effects, we take the shape directly from the Monte Carlo samples after correcting for the difference between PHOTOS and the QED calculation. For the signal shape in $\mathcal{F}$, we use an asymmetric Gaussian function with different widths below and above the mean. All three parameters are determined in Monte Carlo simulation and fixed in the maximum-likelihood fit. The θ_c PDFs are obtained from a sample of approximately 430000 $D^{*+} \to D^0\pi^+$ $(D^0 \to K^-\pi^+)$ decays reconstructed in data, where $K^{\mp}/\pi^{\pm}$ tracks are identified through the charge correlation with the $\pi^{\pm}$ from the $D^{*\pm}$ decay. The PDFs are constructed separately for K^+, K^-, π^+, and π^- tracks as a function of momentum and polar angle using the measured and expected values of θ_c, and its uncertainty. We use the same PDFs for signal and background events.

Table 3 summarizes the fitted signal and background yields, and $K\pi$ charge asymmetries. We find a value of $\mathcal{A}_{K\pi}$ consistent with our previously published result, and a background asymmetry consistent with zero. The signal yields are somewhat higher than the values reported in Ref. [5] due to the removal of the Δt selection requirement and the addition of the radiative tail in the signal ΔE PDF. In order to quantify the effect of FSR on the fitted yields, we perform a second fit using a single Gaussian for the ΔE PDF allowing the mean and width to vary freely. The results are shown in the second column of Table 3, where we find that ignoring FSR lowers the $\pi\pi$ yield by 4.5% and the $K\pi$ yield by 2.4%.

As a crosscheck, in Figs. 1 and 2 we compare the PDF shapes (solid curves) to the data using the event-weighting technique described in Ref. [18]. For each plot, we perform a fit excluding the variable being plotted and use the fitted yields and covariance matrix to determine a weight that each event is either signal or background. The distribution is normalized to the yield for the given component and can be compared directly to the assumed PDF shape. For $m_{\rm ES}$, ΔE, and $\mathcal{F}$, we find excellent agreement for signal $\pi\pi$ and $K\pi$ events (Fig. 1), as well as the sum of all channels for background events (Fig. 2). We have verified separately that the background PDF shapes agree for all three channels. Figure 3 shows the likelihood ratio $\mathcal{L}_S/\sum\mathcal{L}_i$ for all 69264 events in the fitted sample, where $\mathcal{L}_S$ is the likelihood for a given signal hypothesis, and the summation in the denominator is over all signal and background components in the fit. We find satisfactory agreement between data (points with error bars) and the distributions obtained by directly generating events from the PDFs (histograms).

Table 3: Summary of the branching fraction fit using a sample of approximately 227 million $B\overline{B}$ pairs. For comparison, we show the results using a single Gaussian for the signal ΔE PDF, which would correspond to an analysis that ignores FSR effects.

Parameter	Nominal Fit	Ignoring FSR
$N_{\pi\pi}$	491 ± 35	469 ± 34
$N_{K\pi}$	1674 ± 53	1634 ± 52
$\mathcal{A}_{K\pi}$	-0.135 ± 0.030	-0.135 ± 0.030
N_{KK}	3.0 ± 13.1	5.3 ± 12.6
$N_{b\pi\pi}$	32977 ± 194	32998 ± 194
$N_{bK\pi}$	20761 ± 169	20801 ± 169
$\mathcal{A}_{bK\pi}$	0.002 ± 0.008	0.002 ± 0.008
N_{bKK}	13358 ± 126	13356 ± 126

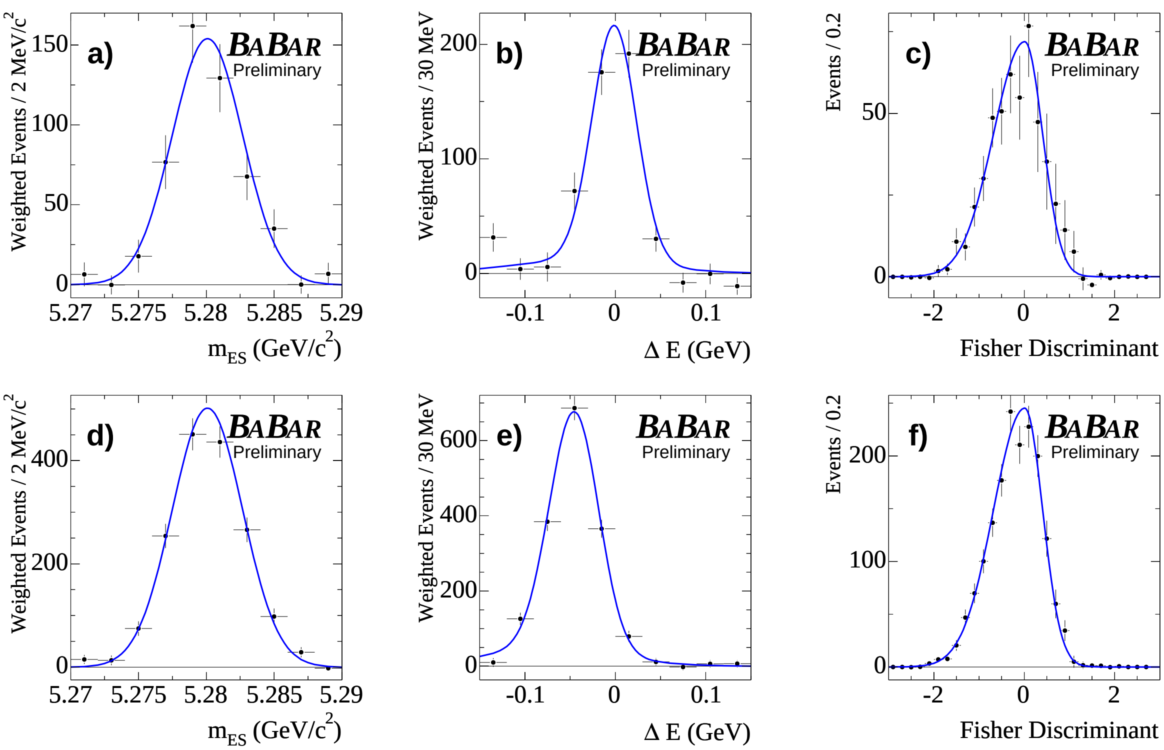

Figure 1: Distributions (points with error bars) of m_{ES}, ΔE, and $\mathcal{F}$ for signal $\pi^+\pi^-$ (a,b,c) and $K^+\pi^-$ (d,e,f) decays using the weighting technique described in Ref. [18]. Solid curves represent the corresponding PDFs used in the fit. The distribution of ΔE for $K^+\pi^-$ events is shifted due to the assignment of the pion mass for all tracks.

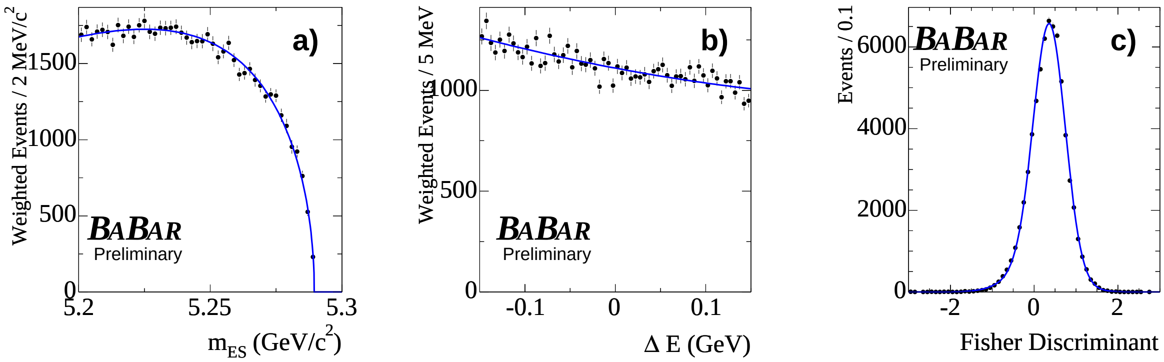

Figure 2: Distributions of a) $m_{\rm ES}$, b) ΔE, and c) $\mathcal{F}$ for $q\bar{q}$ background events (points with error bars) using the weighting technique described in Ref. [18]. Solid curves represent the corresponding PDFs used in the fit.

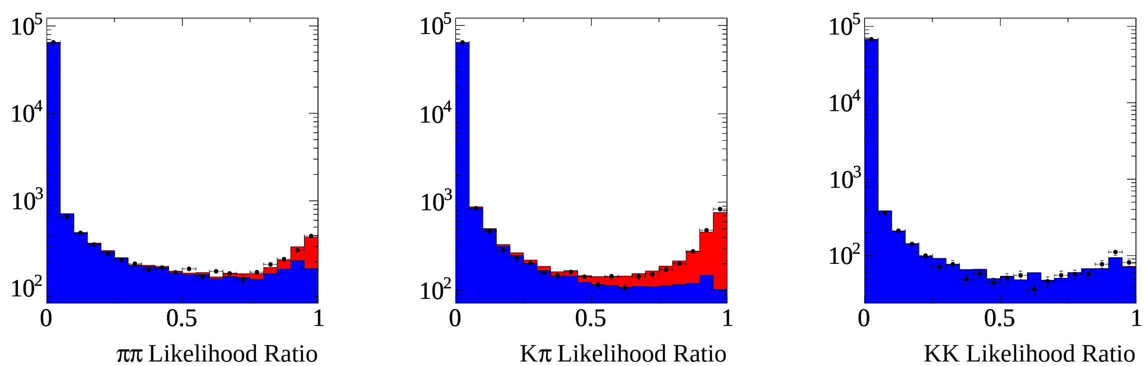

Figure 3: The likelihood ratio $\mathcal{L}_S / \sum \mathcal{L}_i$, where $\mathcal{L}_S$ is the likelihood for each event to be a signal $\pi\pi$ (left), $K\pi$ (middle), or KK (right) event. The points with error bars show the distribution obtained on the fitted data sample, while the histograms show the distributions obtained by generating signal (red) and background (blue) events directly from the PDFs.

Table 4: Summary of relative systematic uncertainties on yields, efficiencies, and number of $B\overline{B}$ pairs. For the K^+K^- yield we show the absolute uncertainty. The total uncertainties for $\pi^+\pi^-$ and $K^+\pi^-$ are calculated as the sum in quadrature of the individual contributions.

Source	$\pi^+\pi^-$	$K^+\pi^-$	K^+K^-
yields	3.8%	1.8%	6.8
efficiency	2.6%	2.5%	2.0%
$N_{B\overline{B}}$	1.1%	1.1%	1.1%
Total	4.7%	3.3%	n/a

4 SYSTEMATIC STUDIES

Systematic uncertainties on the branching fractions arise from uncertainties on the selection efficiency, signal yield, and number of $B\overline{B}$ events in the sample. Uncertainty on the efficiency is dominated by track reconstruction (1.6%) and the effect of FSR (1.3%), which is taken to be the difference between the efficiency as determined in the PHOTOS simulation and the QED calculation (Table 2). Uncertainty on the fitted signal yields is dominated by the shape of the signal PDF for $\mathcal{F}$ (2.9% for $\pi\pi$, 1.5% for $K\pi$) and potential bias (2.2% for $\pi\pi$, 0.9% for $K\pi$) in the fitting technique determined from large samples of Monte Carlo signal events and a large ensemble of pseudo-experiments generated from the PDF shapes. Uncertainties due to imperfect knowledge of the PDF shapes for $m_{\rm ES}$, ΔE, and θ_c are all less than 1%. Table 4 summarizes the total uncertainty on the branching fractions, which is calculated as the sum in quadrature of the individual uncertainties.

5 RESULTS and SUMMARY

Table 5 summarizes the preliminary results for the charge-averaged branching fractions. For comparison, we use the efficiencies and signal yields determined under the assumption of no FSR and find $\mathcal{B}(B^0 \to \pi^+\pi^-) = 5.1 \times 10^{-6}$ and $\mathcal{B}(B^0 \to K^+\pi^-) = 18.1 \times 10^{-6}$, which are consistent with our previously published results [9]. Taking into account FSR effects leads to an increase of the branching fractions by approximately 8% and 6% for $\pi\pi$ and $K\pi$, respectively. The upper limit on the signal yield for KK is given by the value of N_0 for which $\int_0^{N_0} \mathcal{L}_{\rm max}\, dN / \int_0^{\infty} \mathcal{L}_{\rm max}\, dN = 0.90$, corresponding to a one-sided 90% confidence interval. Here, $\mathcal{L}_{\rm max}$ is the likelihood as a function of N, maximized with respect to the remaining fit parameters. We find $N_0 = 25.9$, and the branching fraction is calculated by increasing the signal yield upper limit and reducing the efficiency by their respective total errors (Table 4). For the purpose of combining with measurements by other experiments, we have also evaluated the central value for the branching fraction and find $\mathcal{B}(B^0 \to K^+K^-) = (4 \pm 15 \pm 8) \times 10^{-8}$.

In summary, we have presented preliminary updated measurements of charge-averaged branching fractions for the decays $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$, where FSR effects have been taken into account. We find a value of $\mathcal{A}_{K\pi}$ consistent with the result in Ref. [5], and branching fractions 6-8% higher due to the effect of FSR on the efficiency and signal-yield determination. This difference should be taken into account when comparing with previous measurements of these quantities (Table 1) that do not include these effects. Our results are consistent with current theoretical

Table 5: Summary of branching fraction results in a sample of $(226.6 \pm 1.2) \times 10^6$ $B\overline{B}$ pairs. We show signal yields N_S, total detection efficiencies (ϵ) and branching fractions $\mathcal{B}$ in units of 10^{-6}. The errors are statistical and systematic, respectively, and the upper limit on $B^0 \to K^+K^-$ corresponds to the 90% confidence level.

Mode	N_S	ϵ (%)	$\mathcal{B}(10^{-6})$
$\pi^+\pi^-$	$491 \pm 35 \pm 11$	$39.4 \pm 0.2 \pm 0.9$	$5.5 \pm 0.4 \pm 0.3$
$K^+\pi^-$	$1674 \pm 53 \pm 15$	$38.4 \pm 0.2 \pm 0.8$	$19.2 \pm 0.6 \pm 0.6$
K^+K^-	$3.0 \pm 13.1 \pm 6.8\,(< 25.9)$	$37.6 \pm 0.3 \pm 0.8$	< 0.40 (90% C.L.)

estimates using various techniques [7]. We find no evidence for the decay $B^0 \to K^+K^-$ and set an upper limit of 4.0×10^{-7} at the 90% confidence level.

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